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Energy Deposition in the NuMI Neutrino Beam-Line

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1 Introduction

This Report gives results of energy deposition calculations for LE and ME configurations of the PH2 focusing system in different parts of the beam-line including the beam plug and hadronic hose. The presented information includes also results of calculations of energy distributions in front of the beam absorber.

All results were obtained using the MARS [1] computer code for the 120 GeV resonant extracted primary beam with 4×10^{13} protons per spill. The total energy of a primary beam is equal to 768 kJ or 404 kW in terms of an average power taking into account the 1.9 s repetition period.

2 Description of the Beam-Line

The MARS model of the beam-line includes the focusing system located inside the target pile, the decay region and the beam absorber.

The focusing system includes the target, magnetic horns and the beam plug. The target is defined as a graphite plate with the rectangular cross section. Target lengths and average densities are equal to 0.94 m, 1.20 m and 1.66 g/cm^3, 1.41 g/cm^3 for LE and ME beams respectively. The shapes of inner conductor of horns are described in report [2], the thicknesses of outer conductors are equal to 1” and (1/2)” for the first and second horn respectively. The graphite beam plug [3] has the length of 1.5 m and the diameter of 31.7 mm and is located 1 m downstream the horn1.

The target pile consists of steel and concrete shieldings surrounding the beam-line. The cross section of the target pile, which is shown in Figure 1 corresponds to the cross section from Figure 3-2-17 [4]. The point with coordinates of (X,Y)=(0,0) corresponds to the beam-line axis.

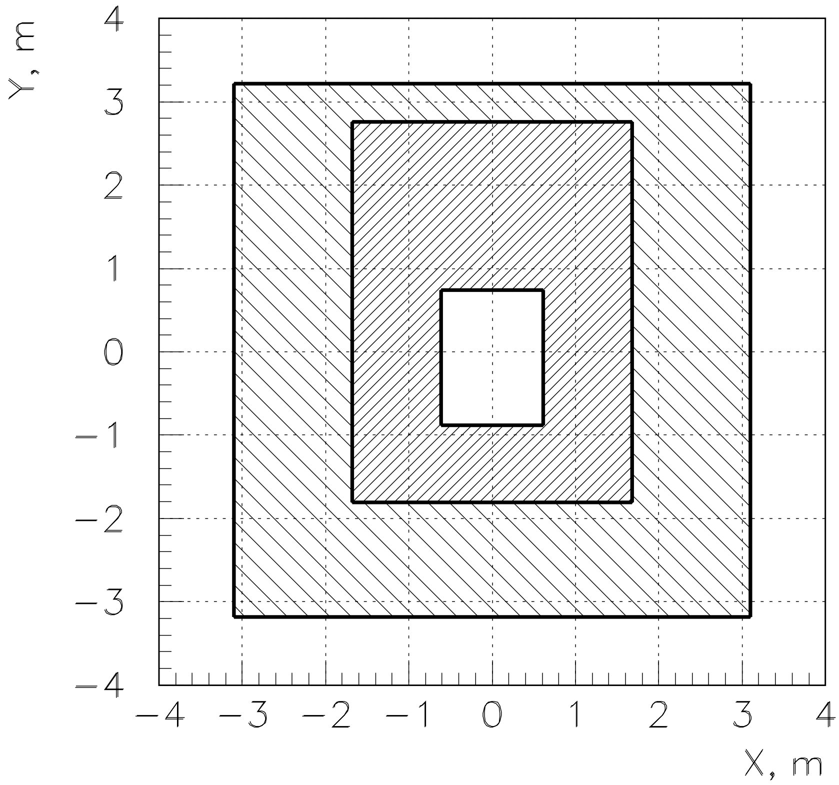

Figure 1: A cross section of the target pile.

The decay region consists of the steel pipe with the inner radius of 1 m and the thickness of (1/2)", concrete shielding surrounding the steel pipe with the outer radius of 4.5 m and the hadronic hose [5] (the 1 mm radius aluminum wire with the current of 1 kA along the decay pipe axis).

The beam absorber [6] consists of the aluminum core with transverse dimensions of 1.32×1.32 m^2 and the length of 2.4 m and steel shielding located around and behind the aluminum core. The total transverse dimensions of the absorber are equal to 3.96×3.96 m^2 and its total length is equal to 3.72 m.

3 Energy Deposition

The main results were obtained for the regular operation mode, when a properly steered primary proton beam interacts with the production target. Besides of the regular operation mode, the incidental operation mode (the emergency), when a primary proton beam does not interact with the target was considered too.

3.1 Regular Operation Mode

Four different configurations of the LE beam-line were considered: OC – the original configuration, HH – the original configuration with the addition of the hadronic hose, BP – the original configuration with the addition of the beam plug, BP HH – the original configuration with the addition of the beam plug and the hadronic hose. Only OC and HH configurations were considered for the ME beam-line. An average power deposited in different parts of the beam-line is given in Table 1.

The Part of the Beam-line	LE–beam				ME–beam	
	OC	HH	BP	BP HH	OC	HH
Focusing System	16.7		24.9		18.3	
target	1.74		1.74		1.49	
horn1 inner conductor	2.17		2.16		1.62	
horn1 outer conductor	10.2		10.2		13.3	
horn2 inner conductor	0.29		0.46		0.15	
horn2 outer conductor	2.32		3.92		1.78	
beam plug	—		6.45		—	
Target Pile	129.8		189.9		144.5	
Decay Region	129.6	163.8	115.3	112.0	112.7	140.3
steel pipe	67.7	81.9	60.7	58.3	58.2	69.6
concrete shielding	61.9	81.5	54.6	53.6	54.5	70.3
hadronic hose wire	—	0.38	—	0.06	—	0.36
Beam Absorber	57.8	21.5	3.97	7.04	58.1	28.3
aluminum core	41.2	14.2	2.31	5.85	40.8	19.4
steel shielding	16.6	7.25	1.66	1.19	17.3	8.90
Total	333.9	331.8	334.1	333.8	333.6	331.4

Table 1: An average power (kW) deposited in different parts of the beam-line in case of the regular operation mode.

Longitudinal distributions of an average power deposited in the target pile, the steel pipe of the decay region and in the hadronic hose wire for different configurations of the beam-line are shown in Figures 2–4. One should note, that:

- The majority of an average power deposited in the target pile (more than 99.9%) is the power deposited in the steel shielding.
- Longitudinal distributions of an average power deposited in the steel pipe of the decay region are essentially different for LE and ME original configurations, as well as for ME OC and ME HH ones (contrary to plots given in Figures 15 and 17 of [7]).
- Longitudinal distributions of an average power deposited in concrete shielding of the decay region are similar to those in the steel pipe for all considered configurations. Moreover, the ratio of total powers deposited in different layers of concrete shielding with radii of $0 < \mathrm{R} < 30\,\mathrm{cm}$, $30\,\mathrm{cm} < \mathrm{R} < 60\,\mathrm{cm}$ and $\mathrm{R} > 60\,\mathrm{cm}$ (zero corresponds to the inner radius of concrete shielding) is $\sim 36:9:1$.
- The energy deposition density in a wire material of the hadronic hose reaches the value of $\sim$3.7 J/cm^3 for LE HH and ME HH configurations.

3.2 Emergency

Three different emergency situations were considered for beam-line with the hadronic hose. These situations differ by characteristics of a primary proton beam at the target position (see Table 2).

Situation	X, mm	X', mrad	Y, mm	Y', mrad
E1 HH	5	0	0	0
E2 HH	5	0.55	0	0
E3 HH	5	0.39	0	0.39

Table 2: Coordinates of a primary proton beam axis at the target position for considered emergency situations.

The results presented in this section correspond to both LE and ME configurations of the PH2 focusing system because in all cases the primary protons pass through field free holes in horn necks.

One should note, that in the absence of the hadronic hose the axis of a proton beam is located in front of the absorber at $R \simeq 40$ cm for both E2 and E3 situations. Contrary to E1 and E2 situations, in case of the E3 one the axis of a proton beam does not cross the hadronic hose wire. This leads to essential redistribution of a power deposition in the decay region and in the beam absorber (see Table 3).

The Part of the Beam-line	The Emergency Situation		
	E1 HH	E2 HH	E3 HH
Decay Region	324.8	321.7	159.8
steel pipe	147.1	145.0	72.8
concrete shielding	175.6	174.6	86.1
hadronic hose wire	2.10	2.05	0.94
Beam Absorber	8.13	15.0	183.9
aluminum core	4.49	8.87	154.8
steel shielding	3.64	6.13	29.1
Total	332.9	336.7	343.8

Table 3: An average power (kW) deposited in different parts of the beam-line for considered emergency situations.

Longitudinal distributions of an average power deposited in the steel pipe of the decay region and in the hadronic hose wire for considered emergency situations are shown in Figure 5.

As it follows from these plots the energy deposition density in a wire material of the hadronic hose reaches the values of $\sim$ 100, 27 and 8 J/cm^3 for E1, E2 and E3 situations respectively.

4 Energy Distributions in Front of the Absorber

Beam energy distributions were obtained for the regular operation mode.

The beam parameters in front of the absorber for all considered configurations of the beam-line are given in Table 4. Radial distributions of the beam energy density and energy spectra of neutrino parents in front of the absorber are shown in Figures 6 and 7 respectively.

As it follows from the Table 4 for the original configurations of the beam-line the main part of an energy is brought to the absorber by non-interacting primary protons, including primary protons passing the target in tails of their x and y distributions. For other configurations of the beam-line the secondaries bring the main part of an energy and the share of $\pi^{\pm}, K^{\pm}$–mesons is equal to 37–45% of an energy of secondaries.

Beam	LE–beam				ME–beam	
Particles	OC	HH	BP	BP HH	OC	HH
Primary protons	107.2	21.6	3.30	2.03	97.0	23.4
Secondaries	14.5	25.4	5.89	14.7	26.2	39.8
p	4.98	8.01	1.40	3.02	8.36	14.5
$\pi^{\pm}, K^{\pm}$	5.00	9.32	2.65	6.66	12.7	18.2
n	2.04	2.31	0.35	0.28	1.85	2.12
$\pi^{\circ} \rightarrow 2\gamma$	0.93	1.03	0.34	0.31	1.13	1.10
$e^{\pm}$	1.56	4.74	1.15	4.45	2.15	3.92
Total	121.7	47.0	9.19	16.7	123.2	63.2

Table 4: A kinetic energy (kJ) of the beam in front of the absorber in case of the regular operation mode.

5 Conclusions

In conclusion one should note, that under energy deposition calculations:

- forced energy deposition for neutrons with the energy less than 20 MeV was used under their production and transport;
- contribution of the muons to energy deposition was not considered.

The first assumption leads to some redistribution of an energy deposited in different layers of concrete shielding, whereas the second one leads to some decreasing of an energy deposited in the beam-line.

A failure of the energy balance (the ratio of the energy of a primary beam to the energy deposited in the beam-line) may be explained also by $\pi^{\pm}, K^{\pm}$–mesons decays, which lead to decreasing of an energy deposited in different parts of the beam-line. Simple calculations show, that in case of the regular operation mode this decreasing is equal to approximately 50 kJ for all considered configurations of the beam-line.

Moreover, a failure of the energy balance in order of $\sim$10% is defined by statistical fluctuations in the processes of particle productions and interactions, which are used in the IHEP MARS code.

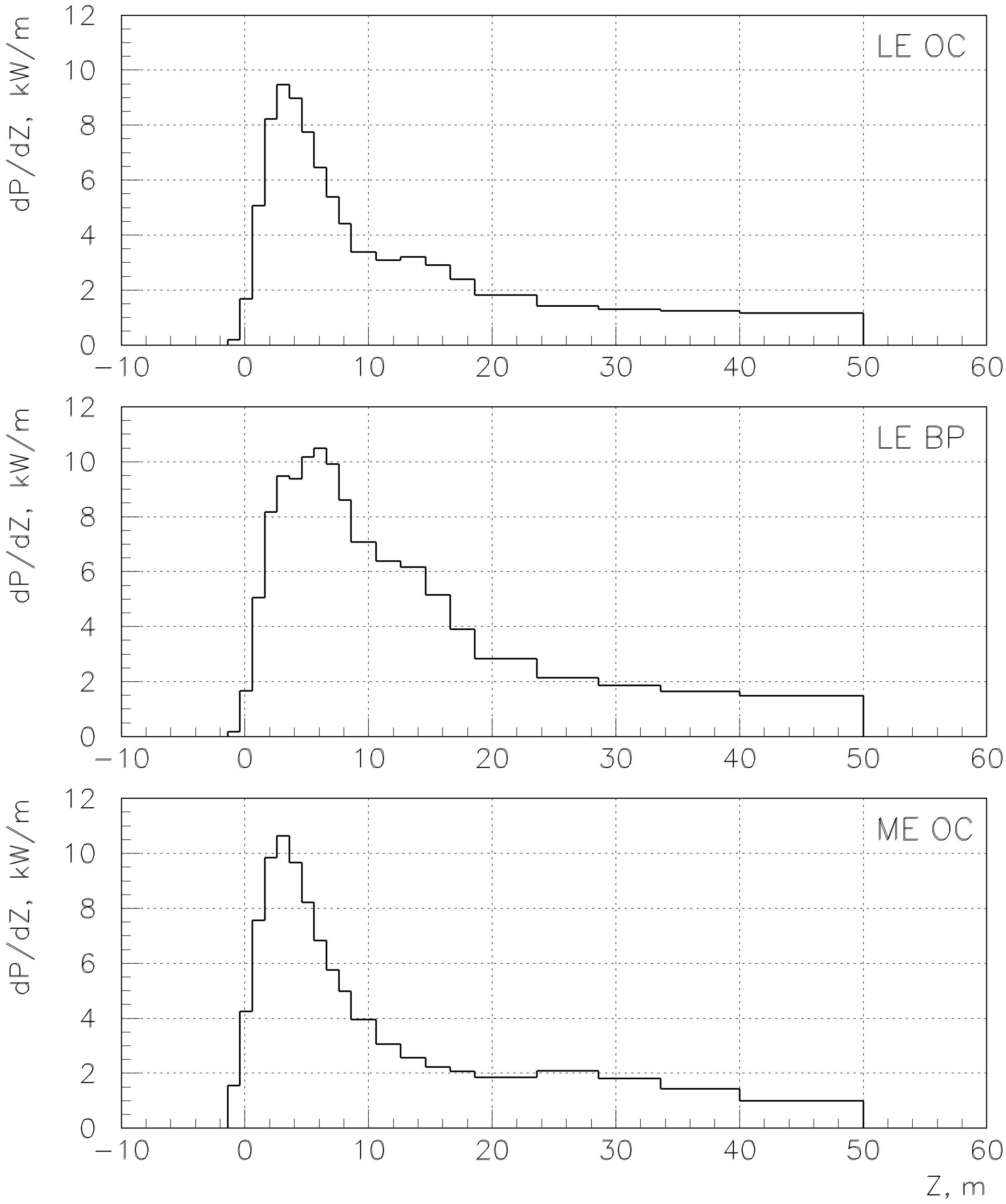

Figure 2: Longitudinal distributions of an average power deposited in the target pile for different configurations of the beam-line in case of the regular operation mode (the upstream end of horn1 corresponds to $Z = 0$).

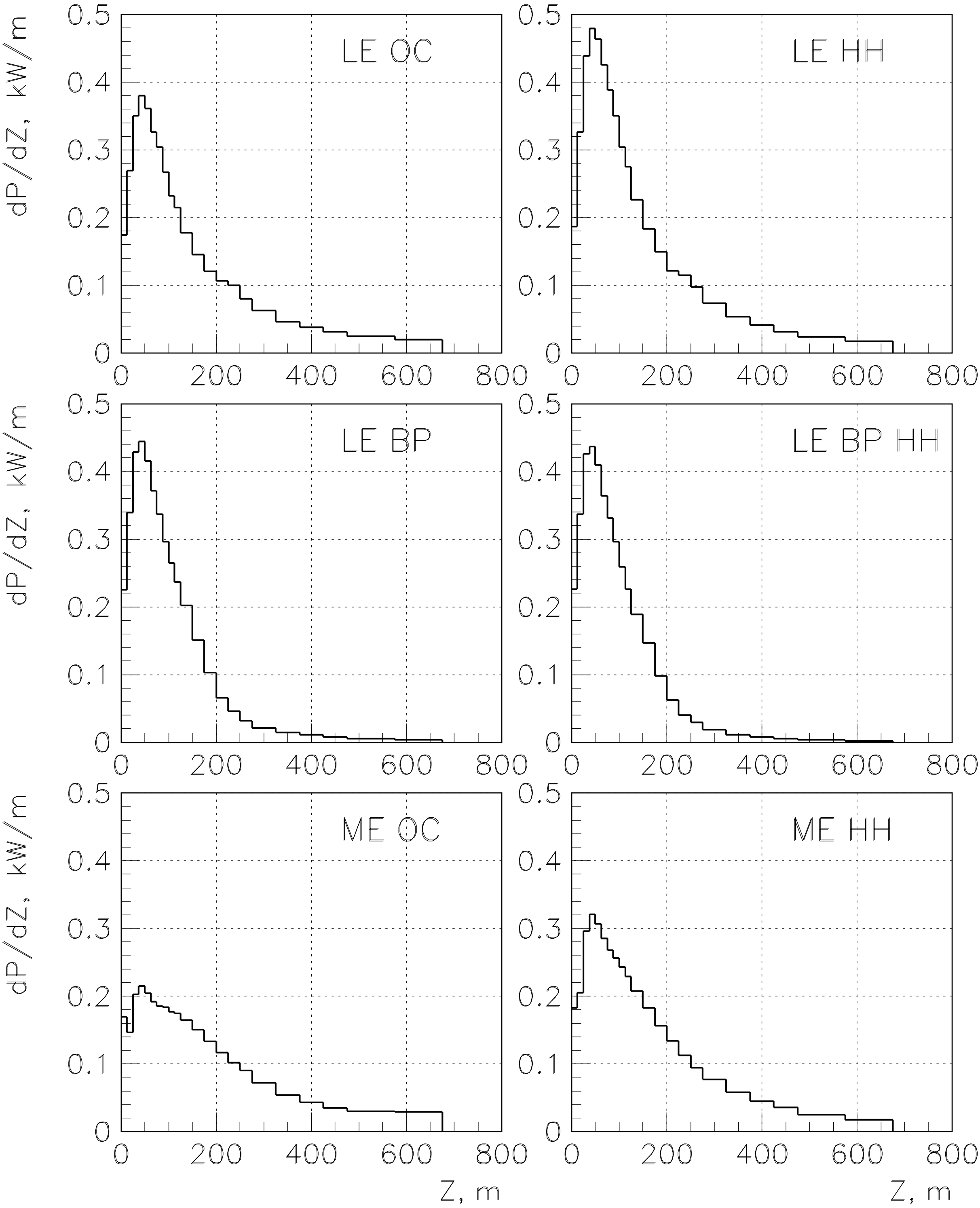

Figure 3: Longitudinal distributions of an average power deposited in the steel pipe of the decay region for different configurations of the beam-line in case of the regular operation mode.

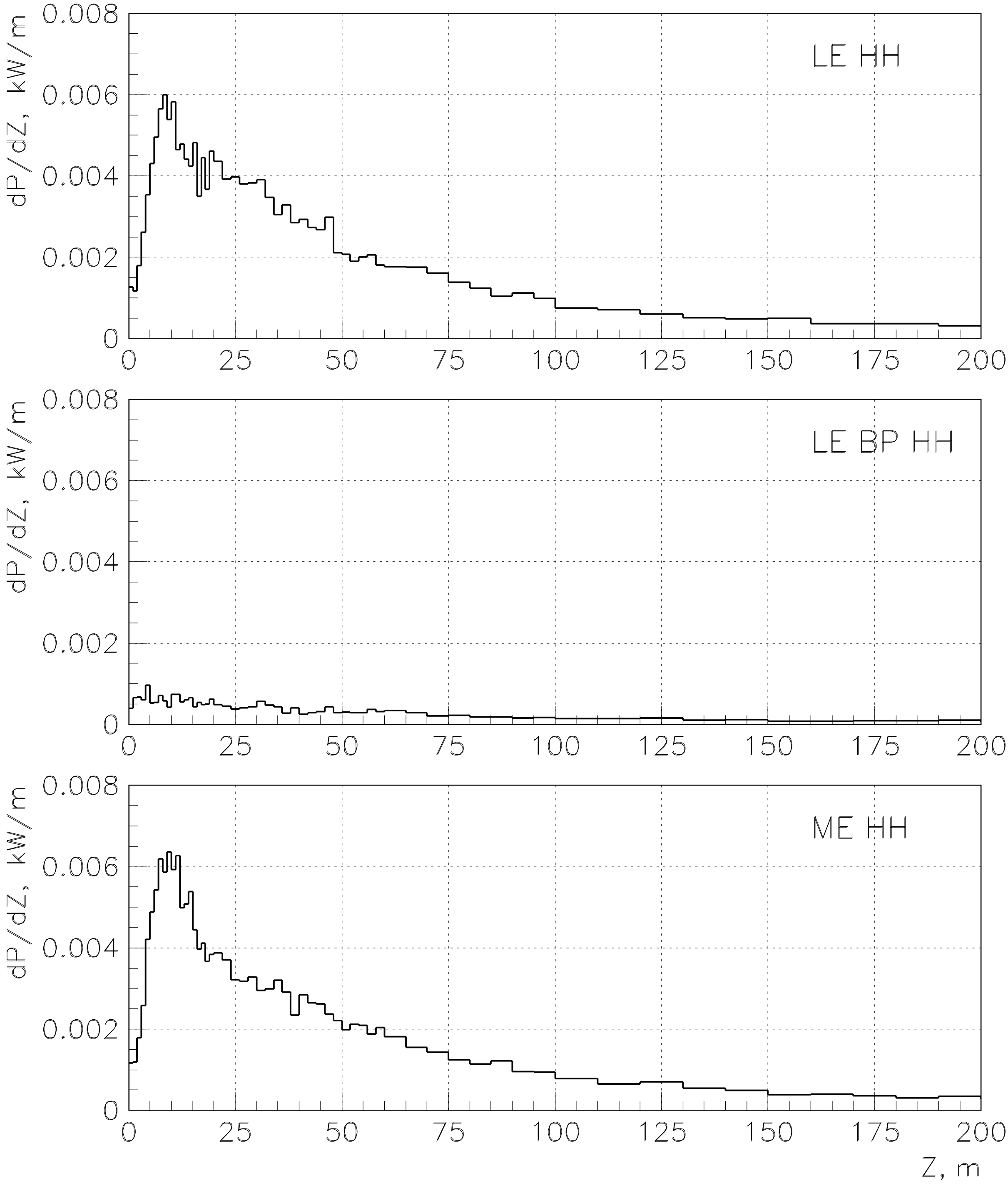

Figure 4: Longitudinal distributions of an average power deposited in the hadronic hose wire for different configurations of the beam-line in case of the regular operation mode.

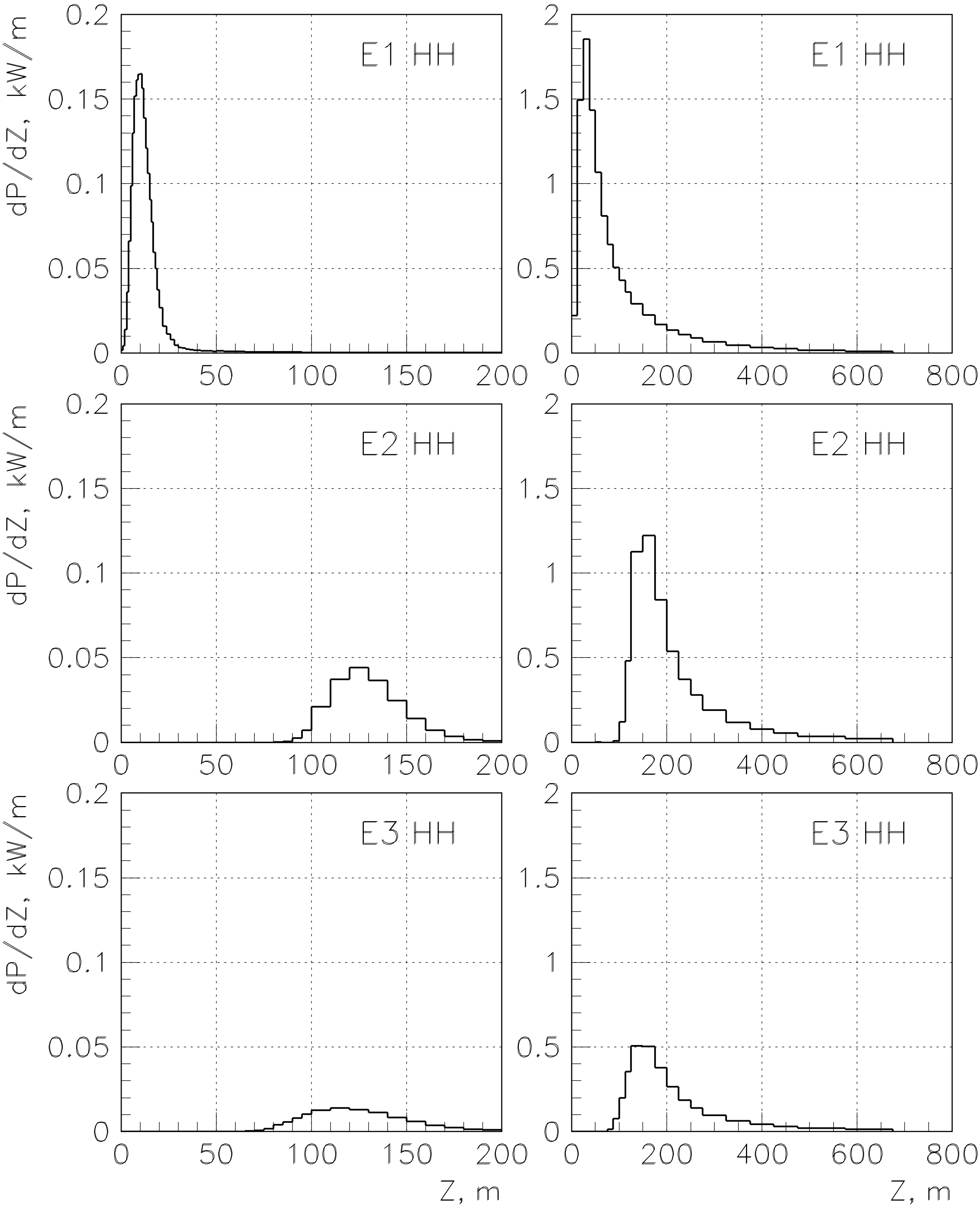

Figure 5: Longitudinal distributions of an average power deposited in the hadronic hose wire (left) and steel pipe (right) in cases of the different emergency situations (see Table 2).

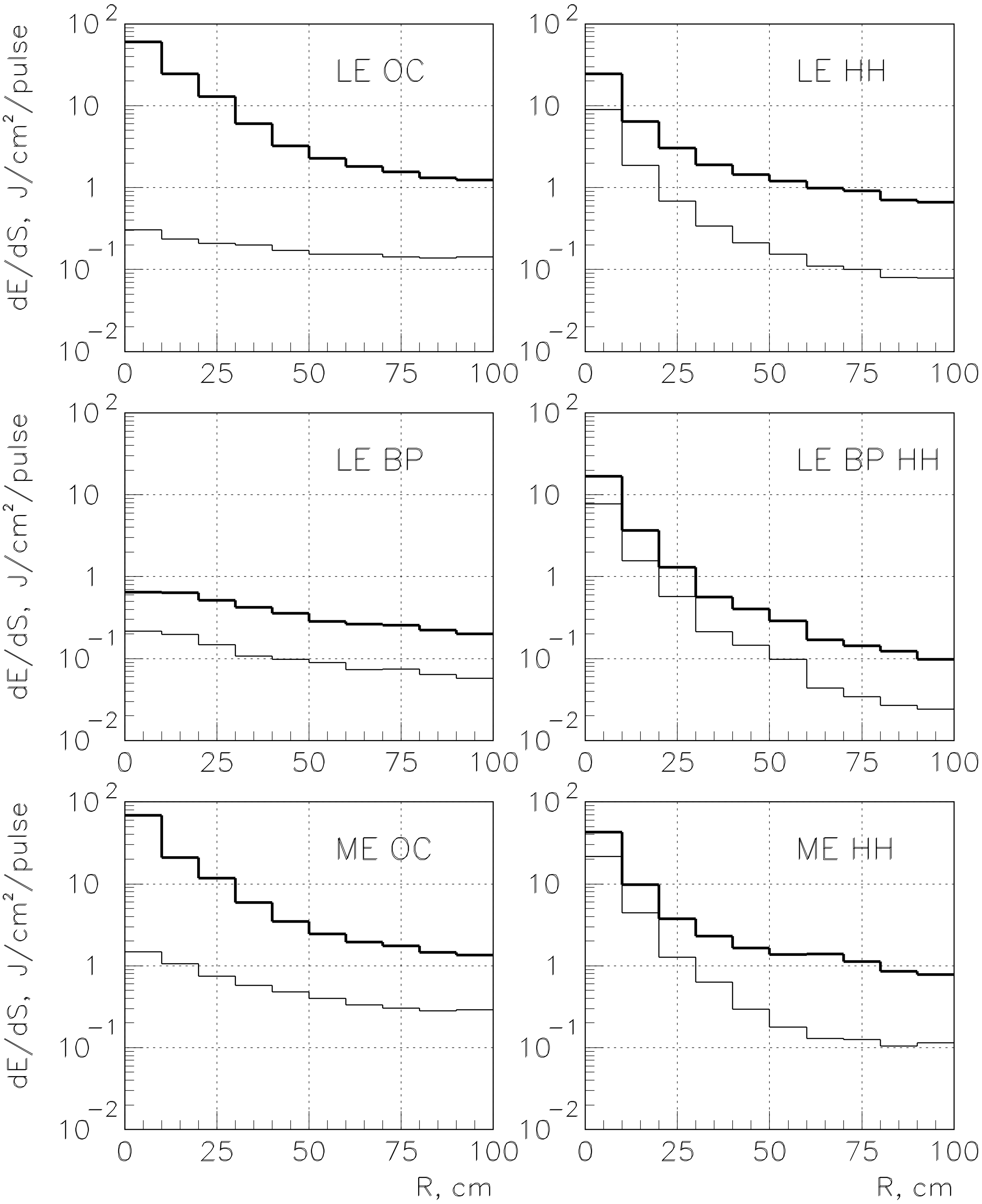

Figure 6: Radial distributions of the beam energy density in front of the absorber for different configurations of the beam-line in case of the regular operation mode: bold line — all particles, thin line — $\pi^{\pm}, K^{\pm}$–mesons.

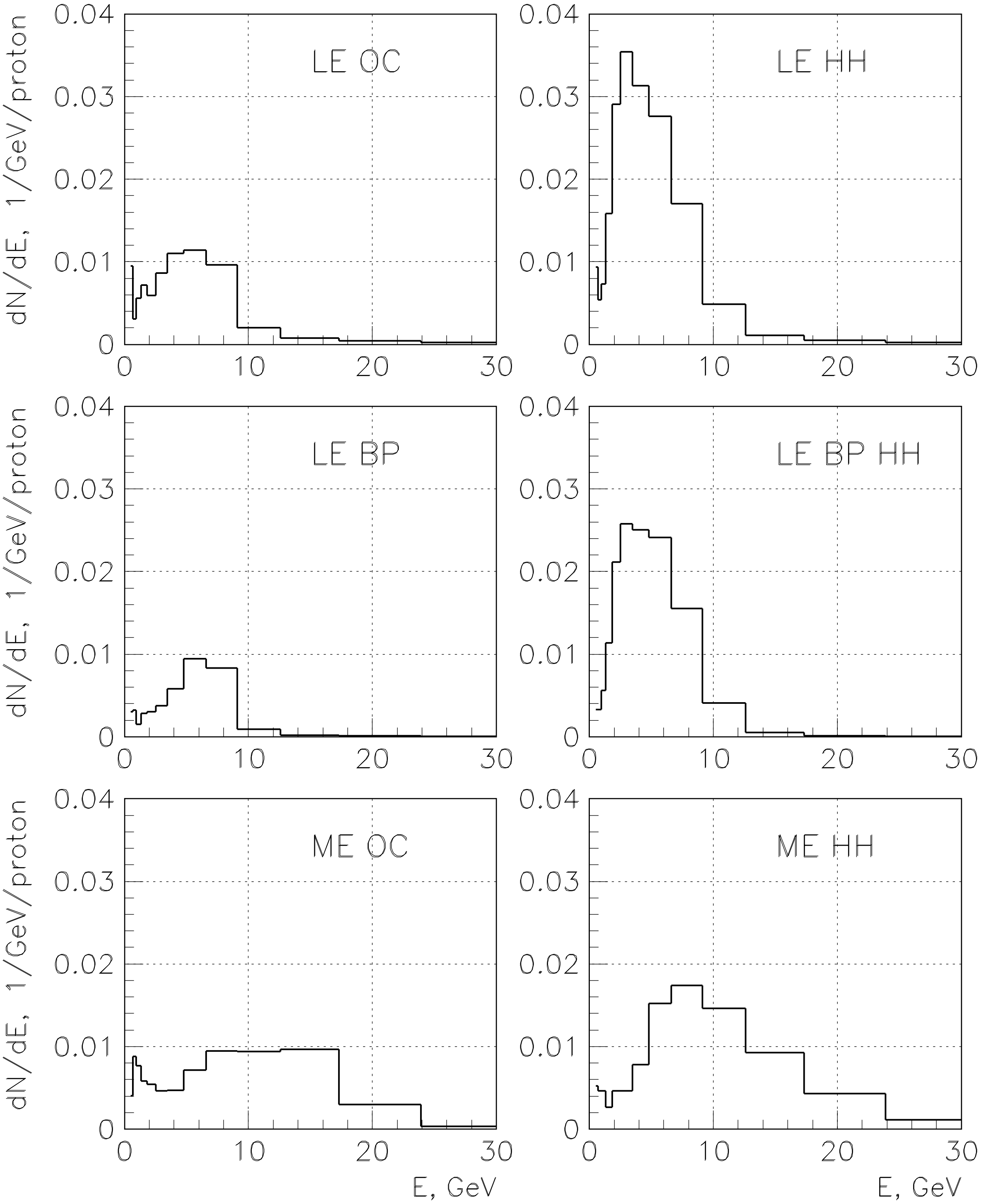

Figure 7: Energy spectra of $\pi^{\pm}, K^{\pm}$–mesons in front of the absorber for different configurations of the beam-line in case of the regular operation mode.

References

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